Nucleon Decay Searches in the past, present, and future

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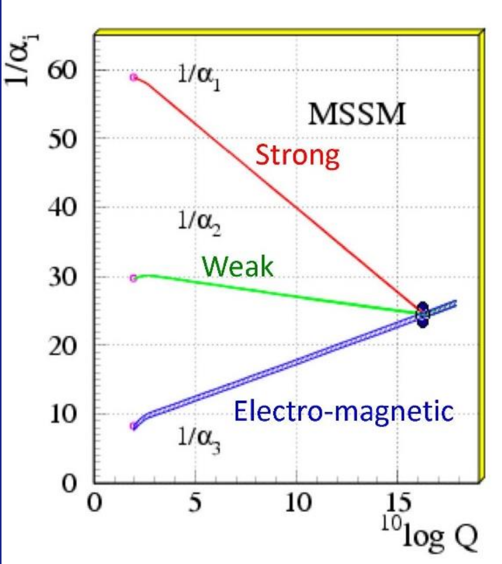
1. Introduction



The Standard Model has been successful!
… but why so many parameters?

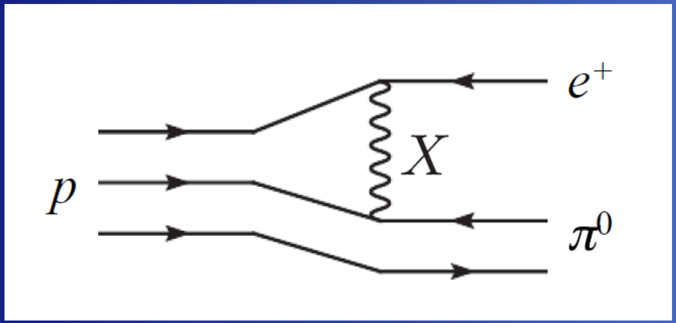
GUTs: attempt to unify Strong and Electroweak interactions.

GUTs scale: $10^{14\text{-}16}$ GeV ⇨ Cannot be reached by Accelerators.

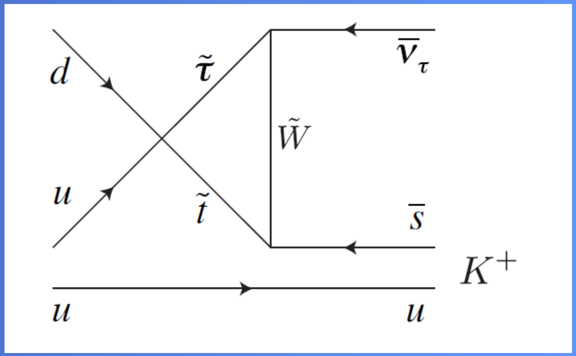
Lepton and baryon numbers are not conserved. ⇨ Proton decay is permitted !

Nucleon decay experiment is the direct probe for GUTs.

Two benchmark decay modes



$p \rightarrow e^+\pi^0$



$p \rightarrow \bar{\nu}K^+$

Proton lifetime predictions

Model	Mode	Prediction (years)
Minimal SU(5)	$p \rightarrow e^+\pi^0$	$10^{28.5} \sim 10^{31.5}$ [1]
Minimal SO(10)	$p \rightarrow e^+\pi^0$	$10^{30} \sim 10^{40}$ [2]
Minimal SUSY SU(5)	$p \rightarrow \bar{\nu}K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [5]

[1] P. Langacker, Phys. Reports 72, 185 (1981)
[2] D.G. Lee, M.K. Parida, and M. Rani, Phys. Rev. D51, 229 (1995)
[3] H.Murayama and A. Pierce, Phys. Rev. D65, 55009 (2002)
[4] T. Goto and T. Nihei, Phys. Rev. D59, 115009 (1999)
[5] V. Lucas and S. Ruby, Phys. Rev. D55, 6986 (1997)

$> 10^{30}$ years !
Need huge detector .

2. Nucleon decay searches before SK

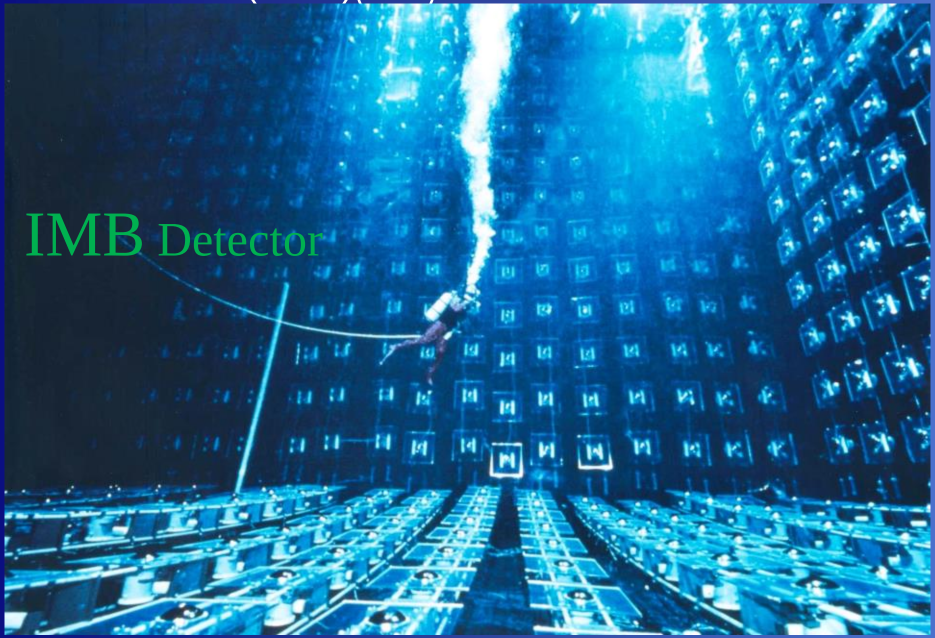
- In the late 1970s, several experiments were proposed.
  - minimal SU(5) prediction: $10^{28} \sim 10^{32}$ years
  - 1kt detector expected $10 \sim 10^3$ decays.
- Background events for proton decay searches are induced by atmospheric ν interactions (they were also ν detectors).
- Two types of detector came into fashion (the 1st generation).

Fine-grained iron calorimeter

- Excellent in track reconstruction.
- Cost per ton were expensive.
- KGF (India), Soudan I,II (Minnesota), NUSEX (Italy/France)

Water Cherenkov detector

- Good momentum resolution and PID.
- Cheaper and easier to build larger detectors.
- HPW (Harvard-Purdue-Wisconsin), IMB (Irvine, Michigan, Brookhaven), Kamiokande



Results of Water Cherenkov detector

Detector	Period	Mass (ton)	Limit ($e^+\pi^0$, 10^{30} yr)
HPW-I	1983-1984	680	1.0
Kamiokande	1983-1997	1040	260
IMB	1982-1992	3300	540

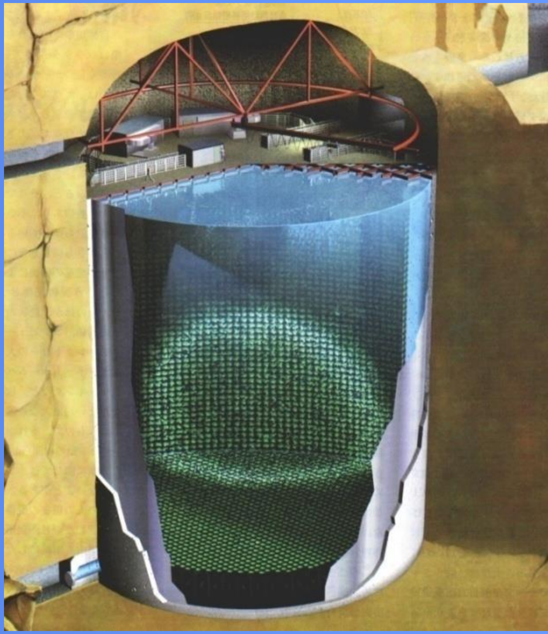
Results of Iron calorimeter

Detector	Period	Mass (ton)	Limit ($e^+\pi^0$, 10^{30} yr)
NUSEX	1982-1998	110-130	15
Frejus	1984-1988	550	70
Soudan I	1981-1990	16-24	1.3

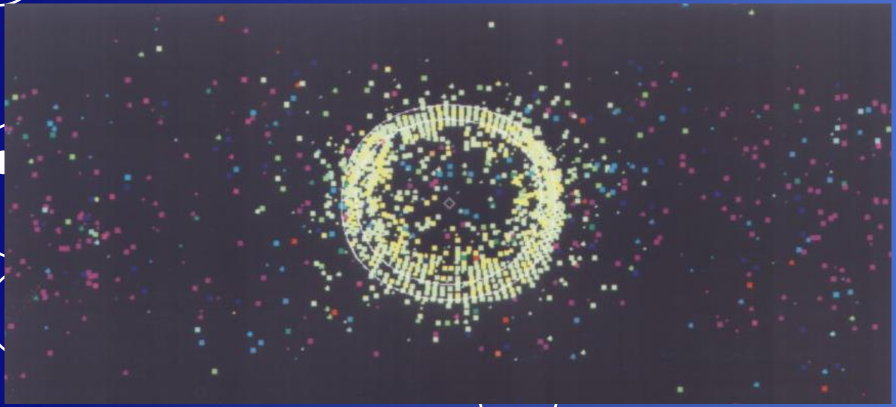
Could not find evidence.
Need more volume.
➔ Super-Kamiokande
(The 2nd generation)

3. Present: Super-Kamiokande

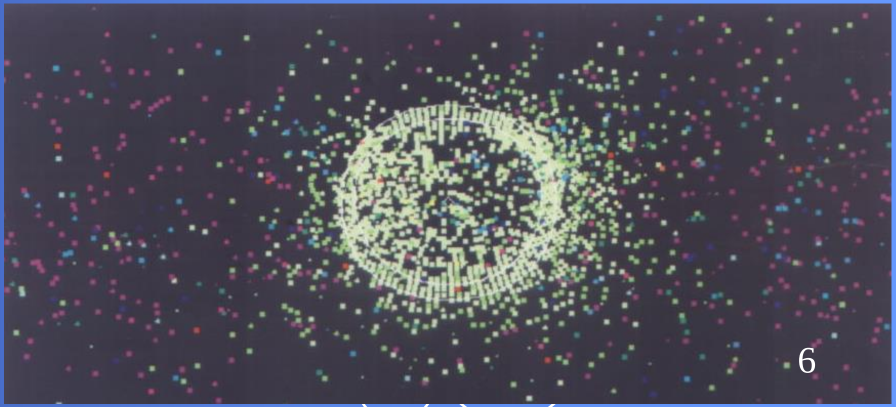
Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water.
Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays, ~1/3 comes from IMB).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.



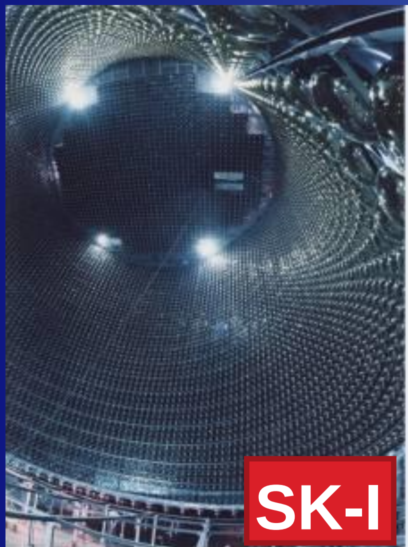
μ-like ($\mu^{\pm}$)



e-like ($e^{\pm}$, γ)

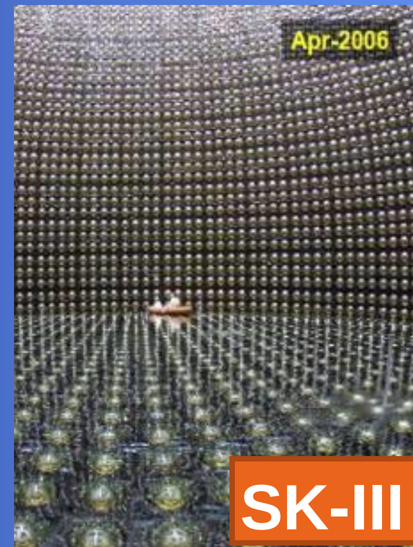


20-year History of Super-Kamiokande



11146 ID PMTs
(40% coverage)

5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

Electronics
Upgrade

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16

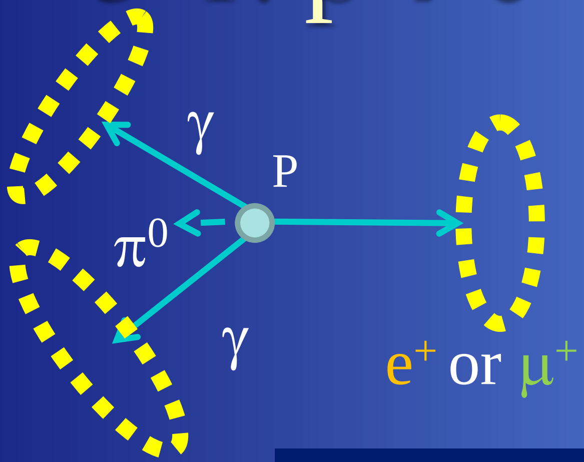
SK-I SK-II SK-III SK-IV

- Still running stably (amazingly!)
- Collected 349 kton・year exposure.

→ Many of the current limits come from SK.

PRD **95**, 12004 (2017)

3-1. $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$ mode



Event features;

- e^+, μ^+ and π^0 are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2\gamma$s : all particles are detectable.

➔ Reconstruct proton mass and momentum.

Selection;

- Fully contained, VTX in fiducial volume.
- 2 or 3 ring

$e^+\pi^0$ case;

- all e-like, w/o decay-e.

Selected by simple cuts!

$\mu^+\pi^0$ case;

- one μ-like with decay-e.

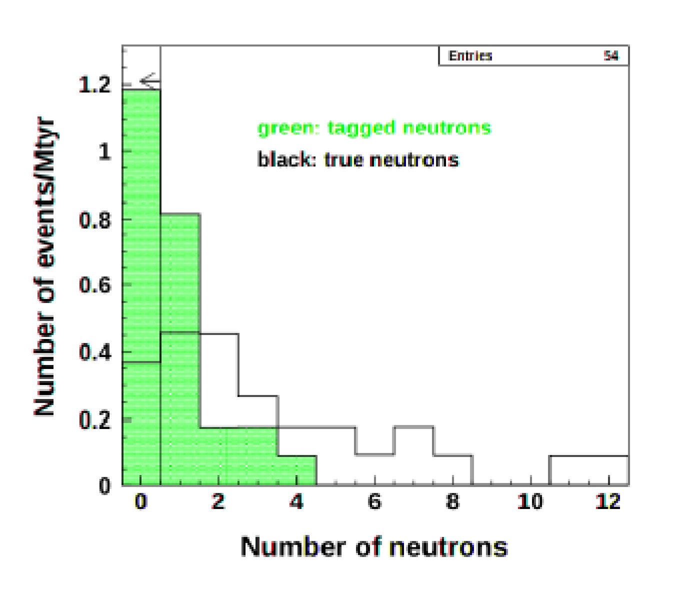
- $85 < M\pi^0 < 185$ MeV (for 3-ring event) .
- $800 < M_P < 1050$ MeV & $P_{tot} < 250$ MeV/c

New technique 1: Neutron tag

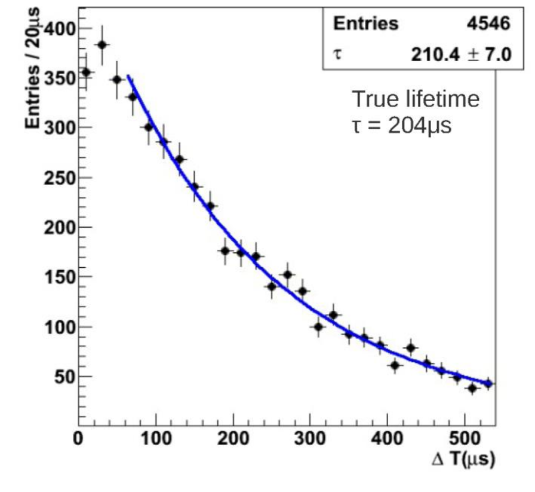
- Most of atmospheric ν BKG are accompanied by neutrons.
- A neutron is captured by a hydrogen (~200μsec) and emits γ ray;

$$n+p \rightarrow d+\gamma \text{ (2.2 MeV)}$$

- New electronics installed in SK4 enables us to record all hits including this γ ray.
- Search for hit cluster N≥7 in 10 ns window after prompt signal, and neutrons are selected by neural network.
- Eff. 20.5 %, BKG 1.8 %.
- About half of the background events can be rejected by requiring no neutron.

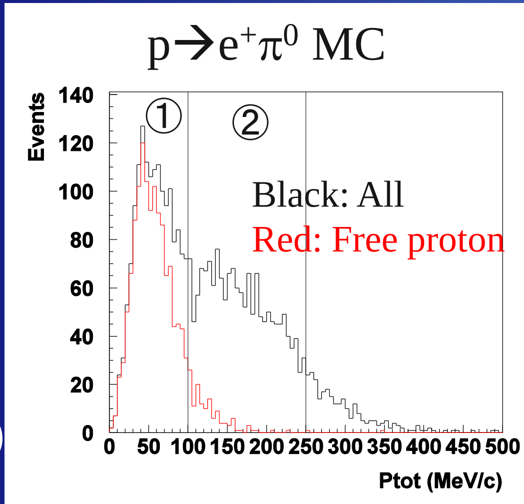


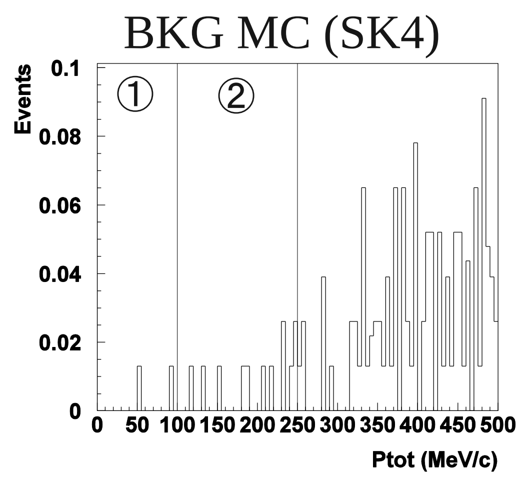
Time difference from prompt signal

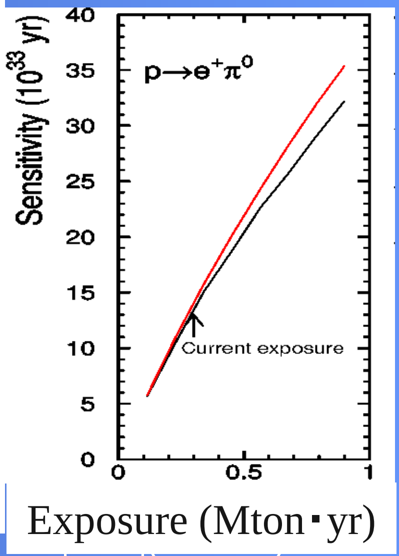


New technique 2: two box analysis

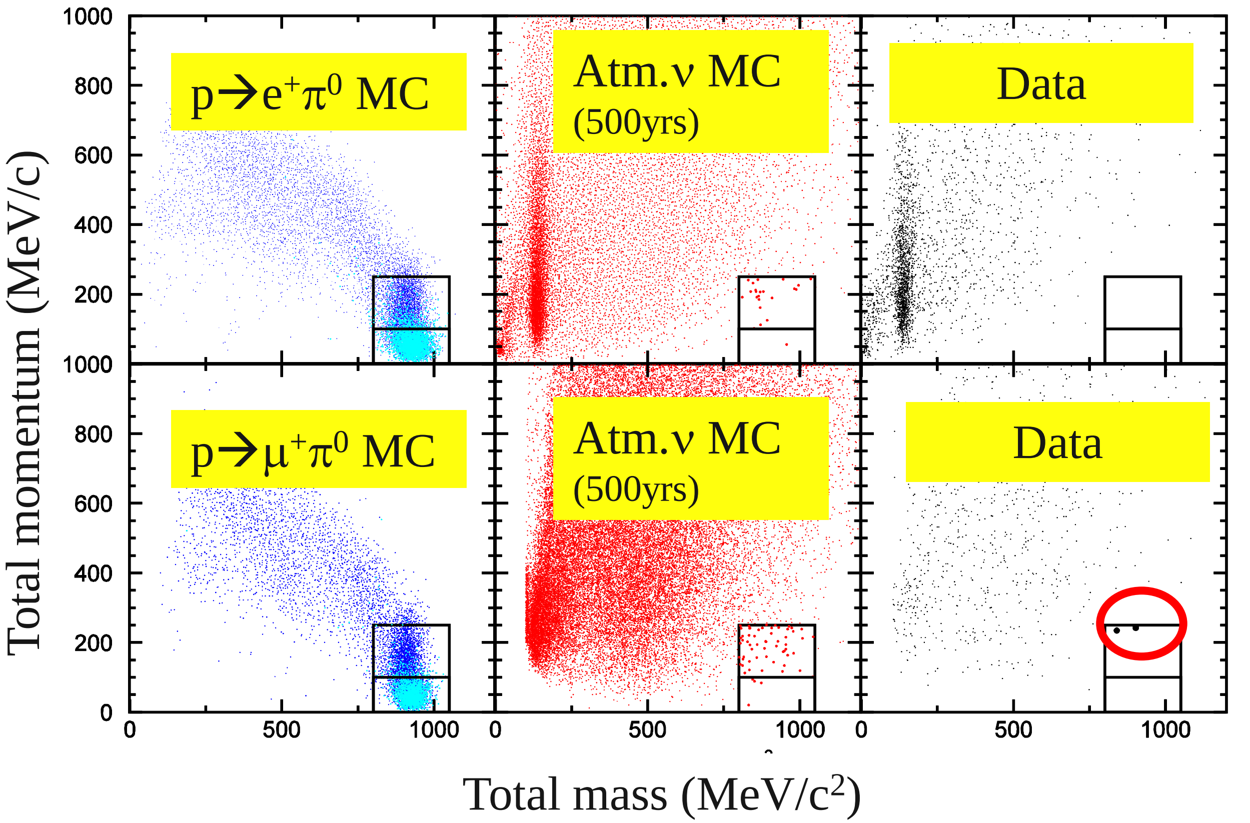
- Signal box defined by $800<M_{tot}<1050$ MeV/c^2 and $P_{tot}<250$MeV/c is divided into two regions;
  - ① Lower box: Ptot<100 MeV/c
    - ✓ Signal: Dominated by free proton(H) decay, free from nuclear effects → Almost BKG free.
  - ② Higher box: 100≤Ptot<250 MeV/c
    - ✓ Signal: Dominated by bound proton (O) decay, more uncertainty due to nuclear effects. More BKG.
- Achieve better sensitivity.







Results



$p \rightarrow e^+\pi^0$

	Eff. (%)	BKG	OBS
Low P_{tot}	18.7	0.07	0
High P_{tot}	19.9	0.54	0
Total	38.6	0.61	0

$p \rightarrow \mu^+\pi^0$

	Eff.(%)	BKG	OBS
Low P_{tot}	18.0	0.05	0
High P_{tot}	16.7	0.82	2
Total	34.7	0.87	2

(Poison(0.87,≥2) = 23%)

Lifetime limt (90% CL,306kton・yrs data)

$p \rightarrow e^+\pi^0$: > 1.6×10^{34} years

$p \rightarrow \mu^+\pi^0$: > 7.7×10^{33} years

3-2. N→ charged anti-lepton +meson

$$\begin{array}{c} p \\ n \end{array} \rightarrow \left(\begin{array}{c} e^{+} \\ \mu^{+} \end{array} \right) + \begin{array}{c} \pi^{0} \\ \eta \\ \rho^{0} \\ \omega \\ \pi^{-} \\ \rho^{-} \end{array}$$

- Several decay modes in which a nucleon decays into a charged lepton and a meson (not only π^0) are proposed.
- Those searches have been studied systematically with 316kton･year data and accepted by PRD (S. Mine (UCI), *et al.*).

Also improved in analysis:

- ✓ Reduce BKG in SK4 by neutron tag.
- ✓ Two box analysis for $p \rightarrow e^{+}/\mu^{+} + \eta^{0}$, $\eta^{0} \rightarrow 2\gamma$
- ✓ And so on .

Event selection

1) Select rings (+ Michel electron cut)

$N \to$	lepton	meson	meson decay mode	(Br.)	
					Primary e/μ ring and
$p \to$	e^+ (μ^+)	π^0	$\pi^0 \to 2\gamma$	(98.8%)	→ 2 e-like rings
$p \to$	e^+ (μ^+)	η	$\eta \to 2\gamma$	(39.3%)	→ 2 e-like rings
			$\eta \to 3\pi^0$	(32.6%)	→ 4, 5 e-like rings
$p \to$	e^+ (μ^+)	ρ^0	$\rho^0 \to \pi^+\pi^-$	($\sim$100%)	→ 2 μ-like rings
$p \to$	e^+ (μ^+)	ω	$\omega \to \pi^0\gamma$	(8.9%)	→ 2,3 e-like rings
			$\omega \to \pi^+\pi^-\pi^0$	(89.2%)	→ 2 e-like and 1 μ-like
$n \to$	e^+ (μ^+)	π^-			
$n \to$	e^+ (μ^+)	ρ^-	$\rho^- \to \pi^-\pi^0$	($\sim$100%)	→ 2-elike and 1 μ-like

2) Reconstruct meson mass

η: 480 ~ 620 MeV/c^2

ρ^0 ,ρ^- : 600 ~ 900 MeV/c^2

ω: 650 ~ 900 MeV/c^2

3) Reconstruct nucleon mass and momentum

mass: 800 ~ 1050 MeV/c^2

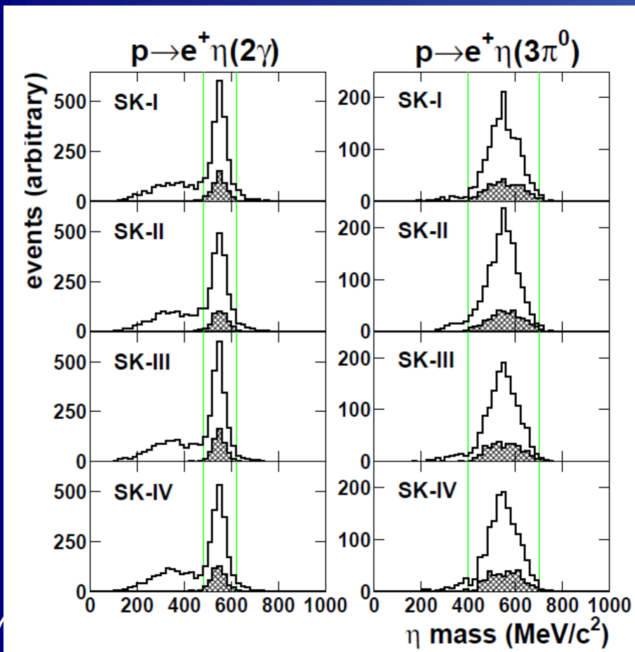
(600~800MeV for p→eω, 450~700MeV for p→μω)

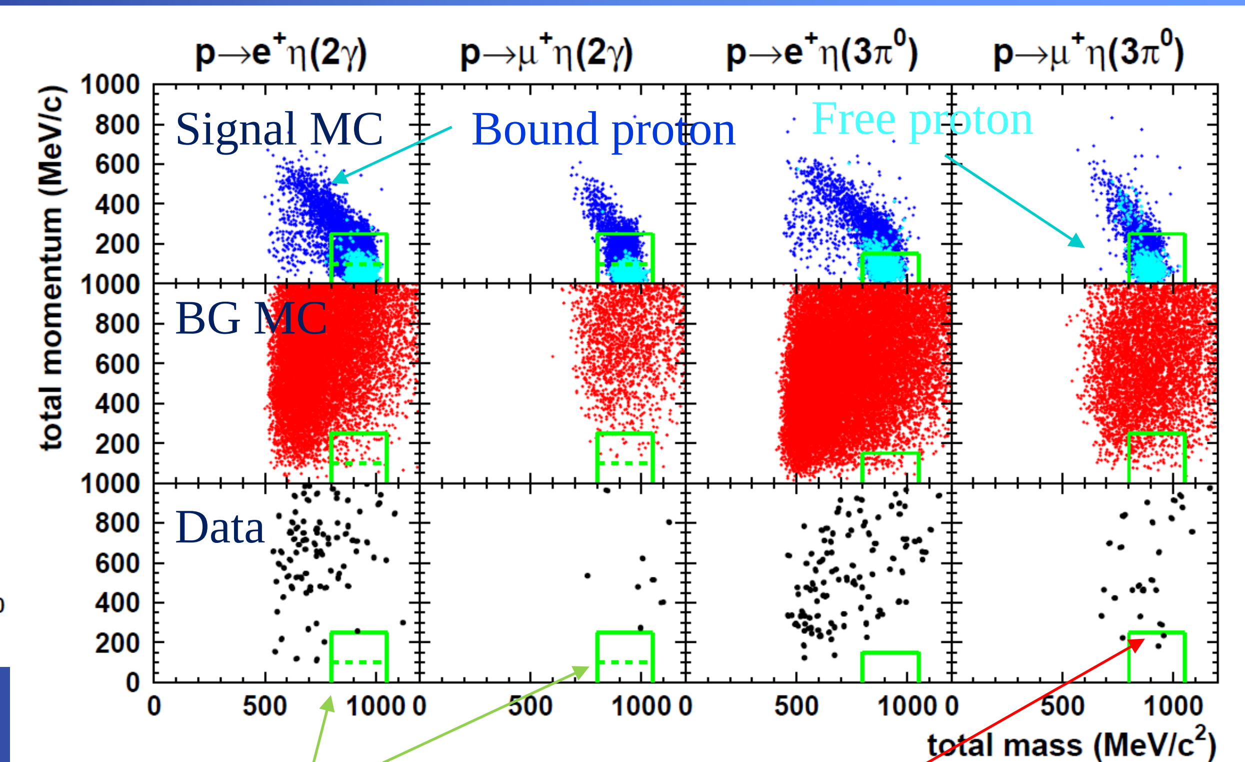
momentum: < 250 MeV/c

(<150 MeV/c for p→eη($3\pi^0$),eρ,eω($\pi^0\gamma$),

<200 MeV/c for p→ε/μω($\pi^+\pi^-\pi^0$)

η mass (Signal MC)   Total mass vs total momentum



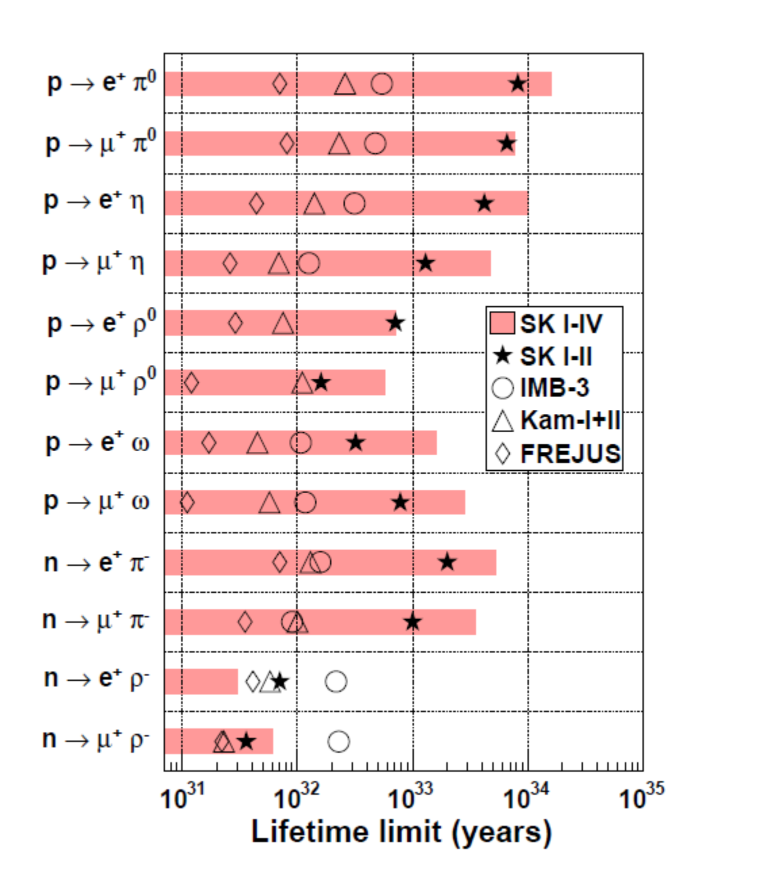


Meson mass can be reconstructed with same quality for all period.

Use two box analysis as same as $p \to e^+\pi^0$.

Two candidates
(expected BG: 0.9 events)

Summary of N→anti-lepton+meson



- Some candidates have been observed, but consistent with expected background.
- Lifetime limits in most modes are improved by factor 2~3 since the previous publication (SK1+2).

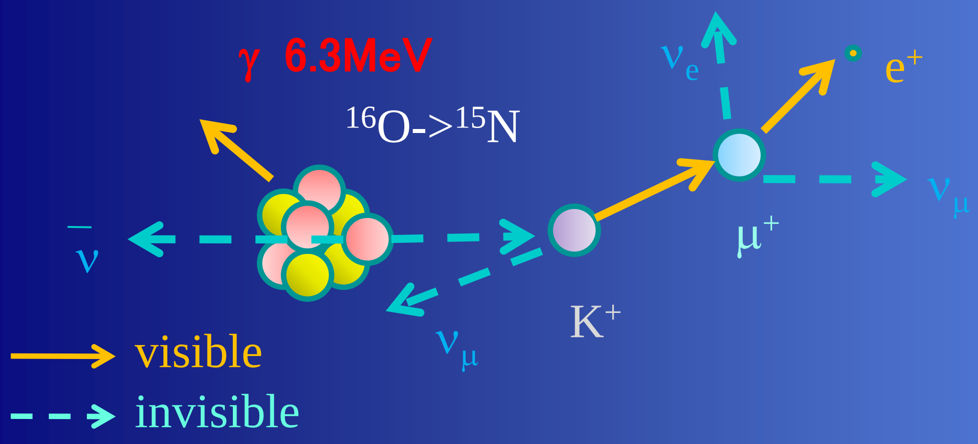
PRD **90**, 072005 (2014) → Updated

3-3. $p \rightarrow \bar{\nu} K^+$ mode

General features

- $\bar{\nu}$ cannot be detected = we cannot reconstruct proton mass and momentum.
- Momentum of K^+ ~ 339MeV/c: below Cherenkov threshold and not visible by SK.
- K^+ stops in water and decay with $\tau = 12\text{ns}$:
  - $K^+ \rightarrow \nu\mu^+$: Br. 64 % (Method A)
  - $K^+ \rightarrow \pi^+\pi^0$: Br. 21 % (Method B)
- In these two body decay case, decayed particles have monochromatic momentum.

Method (A) $K^+ \rightarrow \mu^+\nu_\mu$



Event features;

- K^+ is invisible, stops and 2 body decay (P_μ = 236 MeV/c).

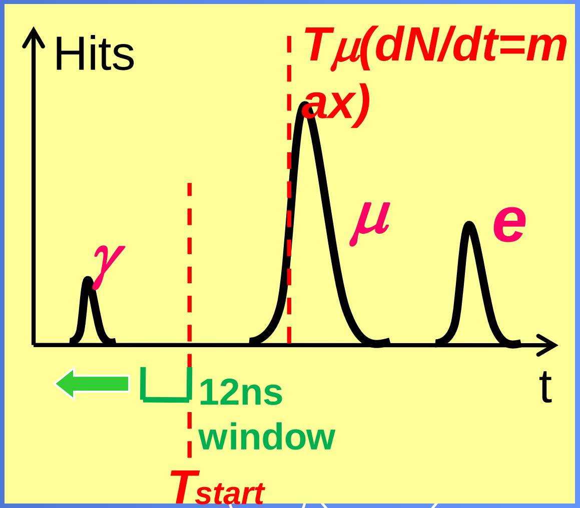
➔ Excess in P_μ.

- Proton in ^{16}O decays and excited nucleus emits 6 MeV γ (Prob. 41%, not clear ring).

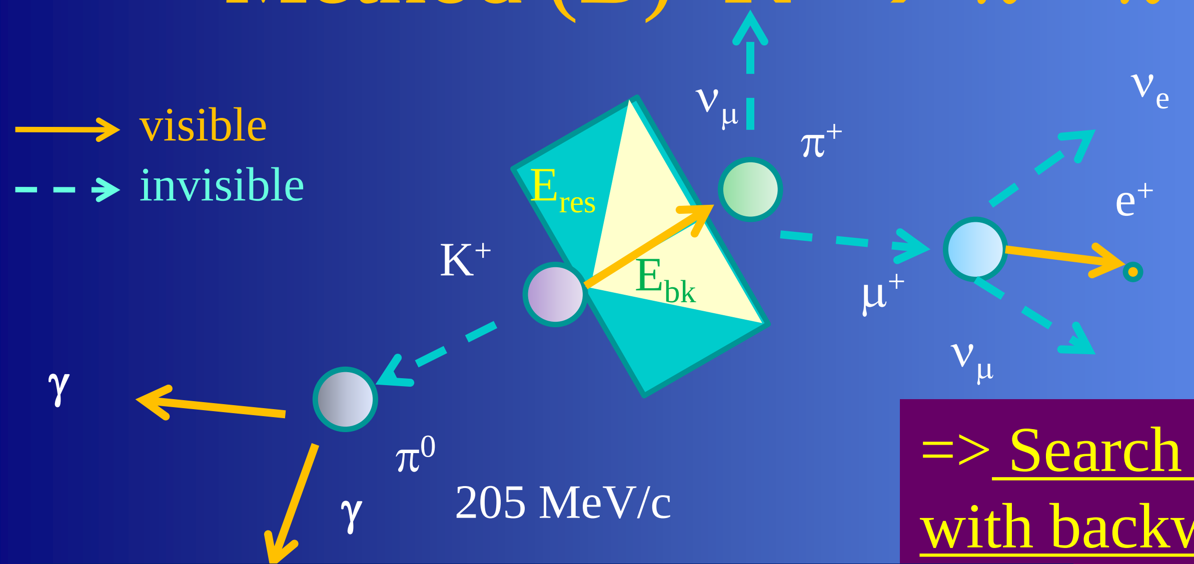
=> Tag γ to eliminate BKG.

Selection:

- 1 μ-like ring with decay-e.
- 215 < Pμ < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < Nγ < 60 hits for SK-1,3,4
    4 < Nγ < 30 hits for SK-2
  - $T_\mu - T_\gamma$ < 75 nsec
- No neutrons (only for SK-4)



Method (B) $K^+ \rightarrow \pi^+ + \pi^0$



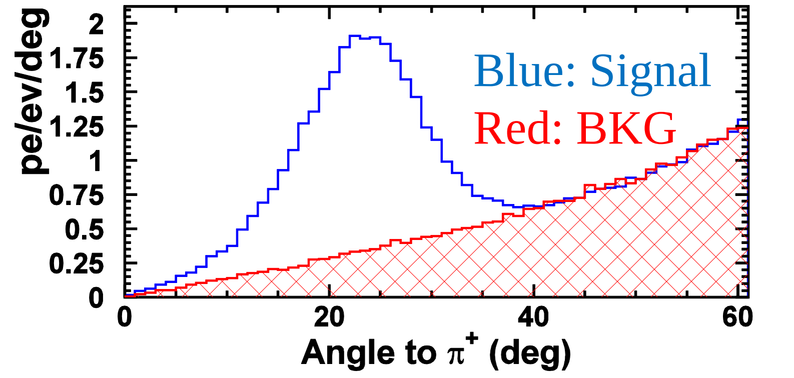
Event features;

- Br. 21 %.
- π^0 and π^+ are back-to-back and have 205 MeV/c.
- $P\pi^+$ is just above Č thres. (not clear ring).

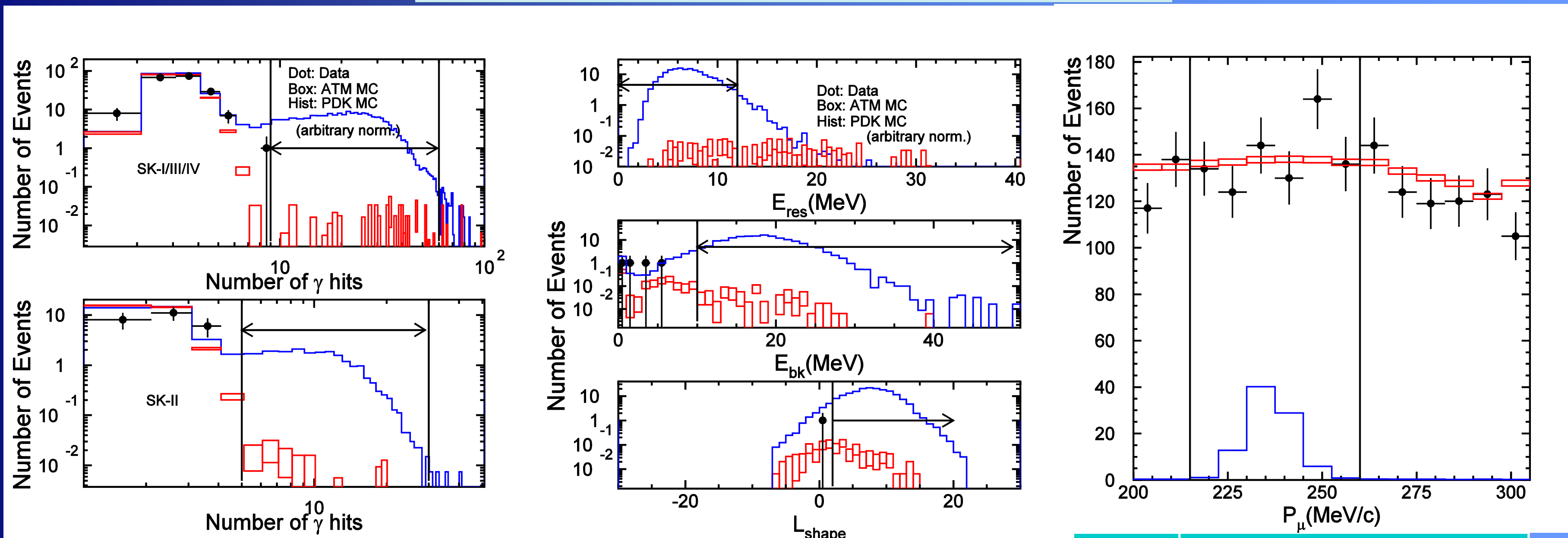
=> Search for monochromatic π^0 with backward activities.

Selection:

- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,
  E_{res}: in 90-140 deg,
  L_{shape}: Likelihood based on charge profile
  $10 < E_{bk} < 50$ MeV
  $E_{res} < 12$ MeV (20 MeV for 1ring)
  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons



No Candidate observed.



	SK1			SK2			SK3			SK4		
	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)
Pr.γ	7.9 ±0.1	0.078	0	6.5± 0.1	0.082	0	7.5 ±0.1	0.018	0	9.4 ±0.1	0.112	0
$\pi^+\pi^0$	7.8 ±0.1	0.21	0	6.5± 0.1	0.19	0	8.3± 0.1	0.07	0	9.6 ±0.1	0.13	0

$p \rightarrow \nu K^+$ Lifetime limit (90% CL) :

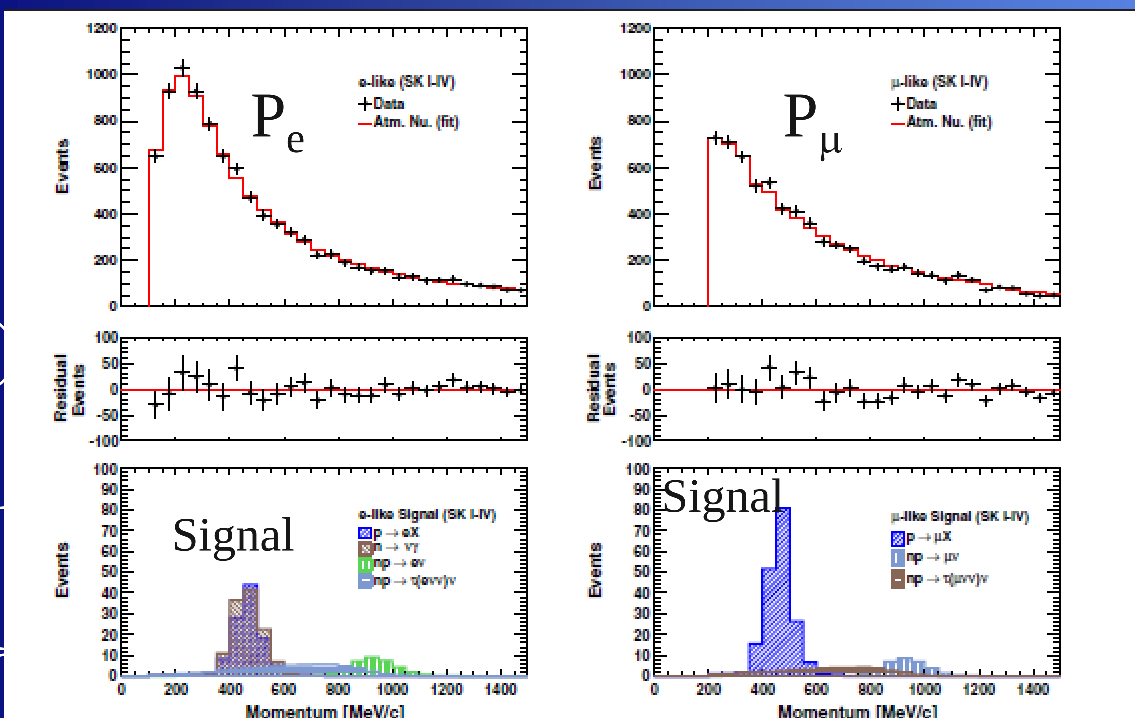
$> 8.0 \times 10^{33}$ yrs (349 kton・yr exposure)

3-4 Other decay modes

V. Takhistov (UCI), *et al.*, PRL **115**, 121803(2015)

N (NN)→ charged lepton +X

- Search for
  - ➢ p→ e^+/μ^+ + X, n→γ+X (X: invisible massless particle, ΔB=1)
  - ➢ pn→$e^+/\mu^+/\tau^+$ + ν (di-nucleon decay, ΔB=2)
- Test momentum distributions of single ring events.



- Data and Atm.ν MC agree well.
- Lifetime limits: fit data by Atm.ν and signal MC.
- ➢ p→e^+X: > 7.9x10^{32} yrs
- ➢ p→μ^+X: > 4.1x10^{32} yrs
- ➢ n→γX: > 5.5x10^{32} yrs
- ➢ pn→e^+ν: > 2.6x10^{32} yrs
- ➢ pn→μ^+ν: > 2.2x10^{32} yrs
- ➢ pn→τ^+ν: > 2.9x10^{32} yrs

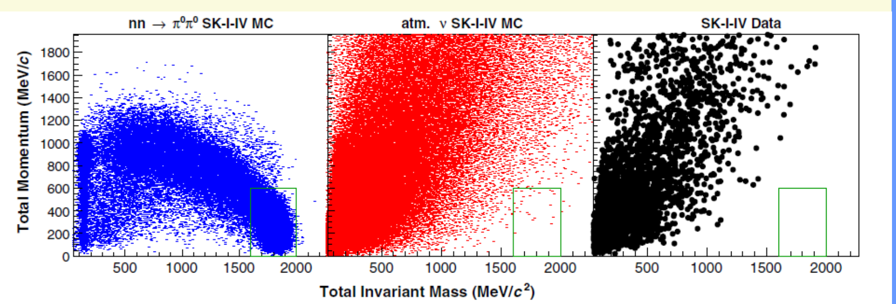
J.Gustafson (BU), *et al.*, PRD **91**, 072009 (2015)

Di-nucleon decays: NN→ ππ

- Search for $^{16}O(pp) \rightarrow {}^{14}C\pi^+\pi^+$, $^{16}O(pn) \rightarrow 14N\pi^+\pi^0$, $^{16}O(nn) \rightarrow {}^{14}O\pi^0\pi^0$.
- $\Delta B=2$
- Tag pions in back-to-back. Pions are affected by nuclear interactions in nucleus and water.
  - Use Boosted Decision Tree for $pp \rightarrow \pi^+\pi^+$ and $pn \rightarrow \pi^+\pi^0$
- For $nn \rightarrow \pi^0\pi^0$, use total mass and total momentum cuts, as same as $p \rightarrow e^+\pi^0$.

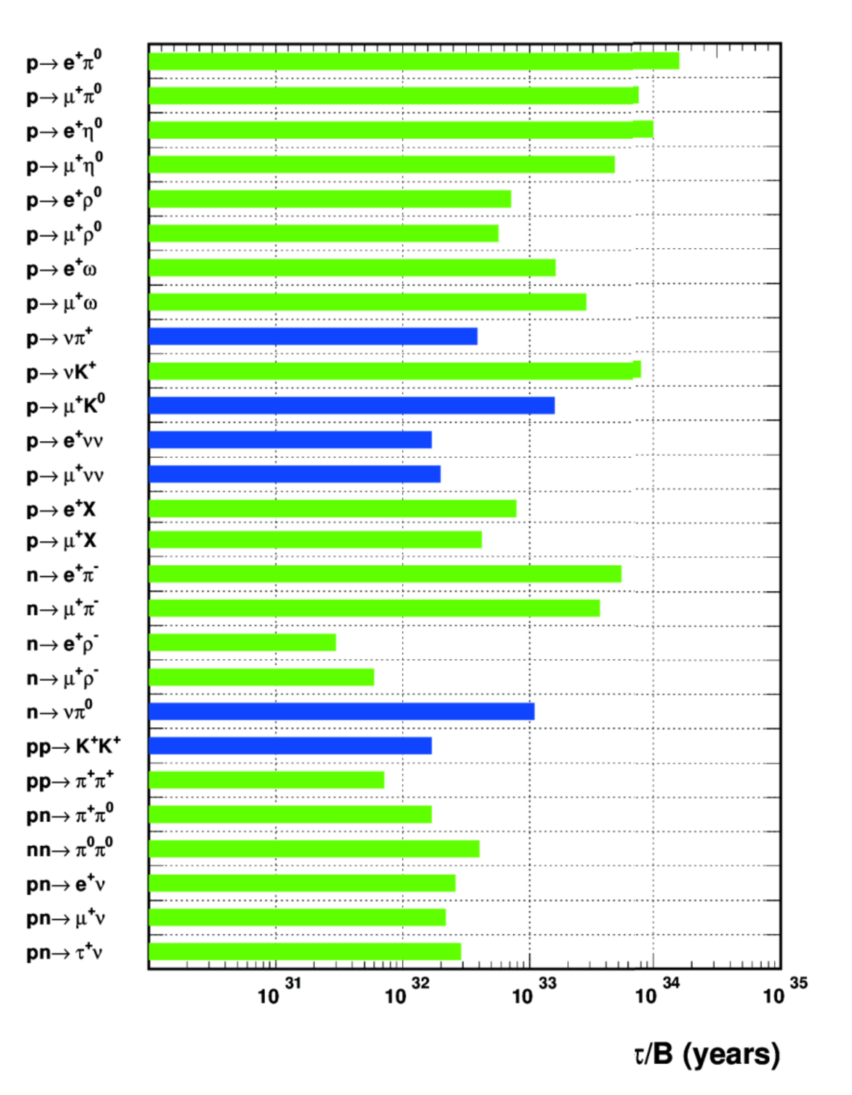
Mode	Eff.(%)	BKG	Obs	Limit (10^{32}yr)
$pp \rightarrow \pi^+\pi^+$	5.9	4.5	2	0.72
$pn \rightarrow \pi^+\pi^0$	10.2	0.75	1	1.7
$nn \rightarrow \pi^0\pi^0$	21.1	0.14	0	4.0

Mtot vs Ptot for $nn \rightarrow \pi^0\pi^0$



Observation is consistent with BKG.

3-5. Summary of the current results

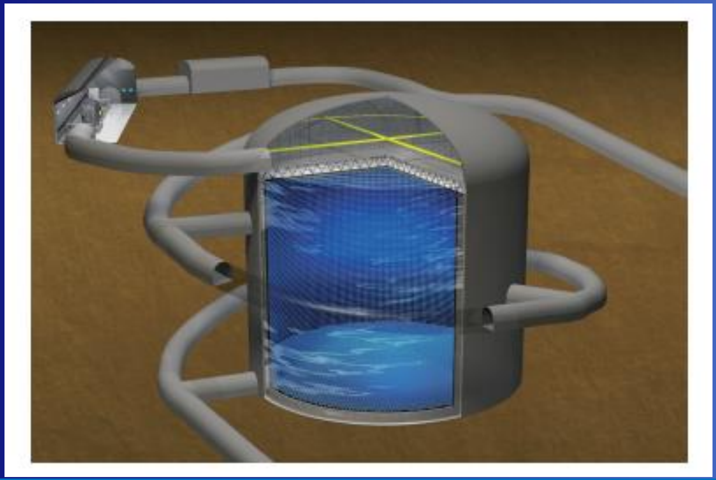


- Most of modes have been investigated with > 0.3 Mton · year exposure (green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- Many of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidence of nucleon decay has been observed.

4. Future prospects

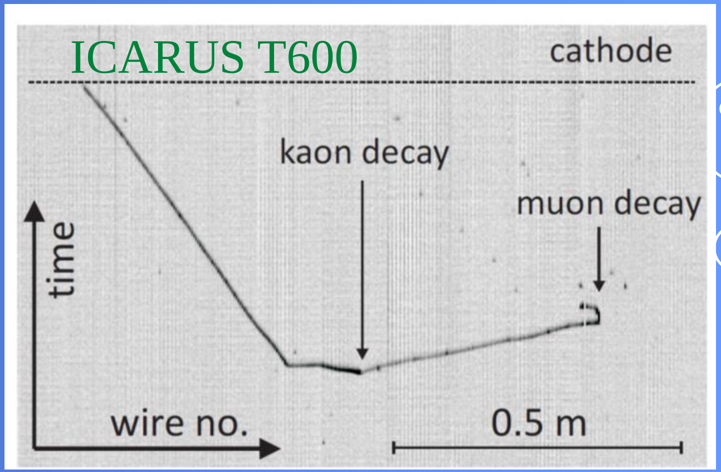
- Still no evidence has been found. Major decay modes are explored up to around 10^{34} years.
- Proton lives longer, ~10^{35} years ?
  - Run SK 10 times more (~200 years)? → Impossible.
  - Need "the 3rd generation" detectors.
- Several projects are moving forward.
  - Water Cherenkov: Hyper-Kamiokande (HK)
    - ✓ Well established and stable.
    - ✓ Larger volume.
    - ✓ Can cover several decay modes.
  - New wave: DUNE (LAr), JUNO (L-Scintillator)
    - ✓ Excellent event reconstruction.
    - ✓ High efficiency, low background.

Hyper-Kamiokande



- Tank size: 60m (H)x74m(D), 186 kton , upright cylindrical.
- Start budget request for the first tank.
- 40 % photo coverage by new Box&Line PMT (photon counting eff. ×2, ½ time resolution than SK PMT).
- Can achieve better neutron tagging efficiency which rejects Atm.ν BG.

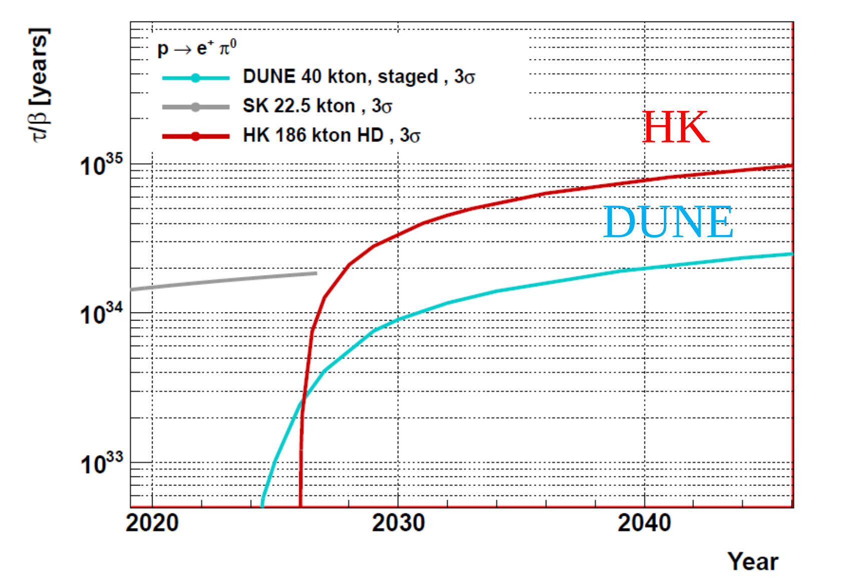
DUNE



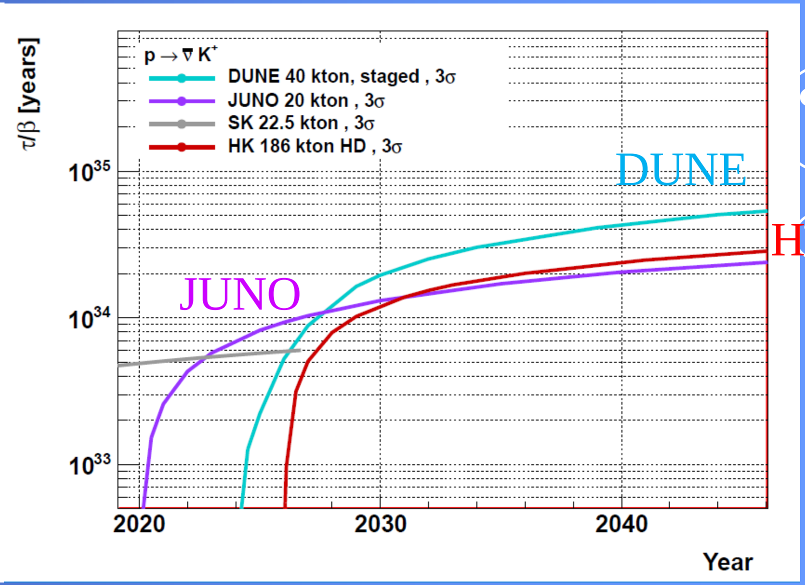
- Liquid Ar TPC, start from 10 kton, increased up to 40 kton later.
- Can reconstruct K^+ track.
- Efficiency for $p \rightarrow \nu K^+$: 97 %, ~4 times more than HK.
- Efficiency for $p \rightarrow e^+\pi^0$ is limited by π interaction in nucleus and similar to HK.

3σ discovery potential by future detectors

$p \rightarrow e^{+}\pi^{0}$



$p \rightarrow \bar{\nu}K^{+}$

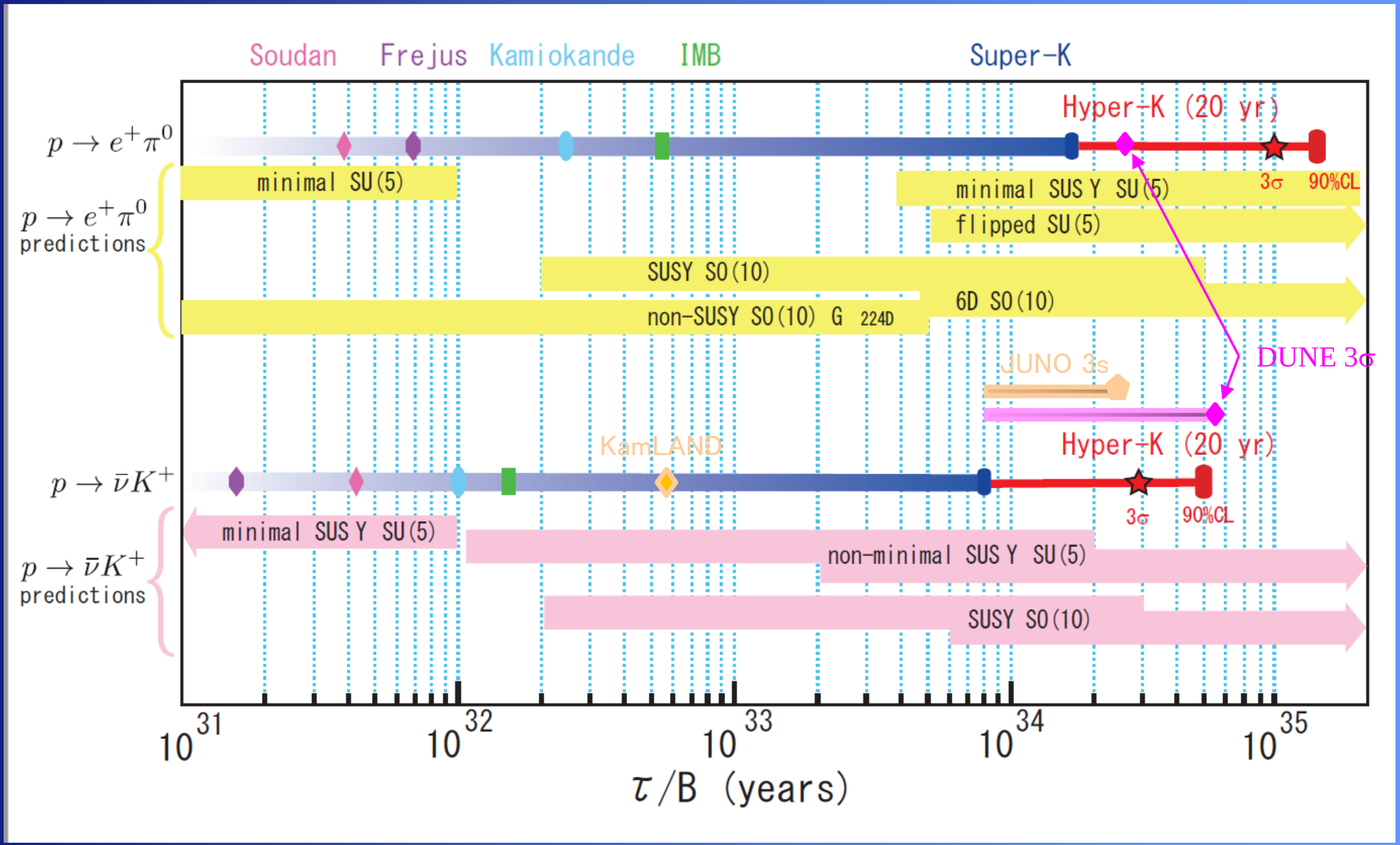


	Eff(%)	BG/Mton
HK	38.1	0.7
DUNE	45	1.0

	Eff(%)	BG/Mton
HK	23.5	1.6
DUNE	97	1.0
JUNO	65	2.5

Numbers are taken from Design Report.
Systematic error included only in HK case.

Comparison with Predictions



Future experiments will cover most of predicted region (the third time's a charm !).

Thank you, UCI !

- UCI have been contributing Nucleon Decay Searches for long time. We really appreciate your great efforts !

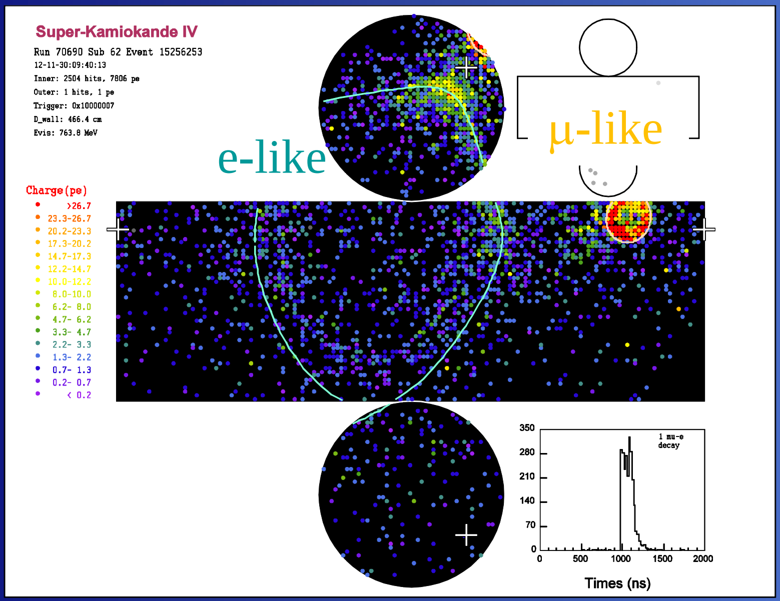
Backup

Water Cherenkov Detector for Nucleon Decay searches

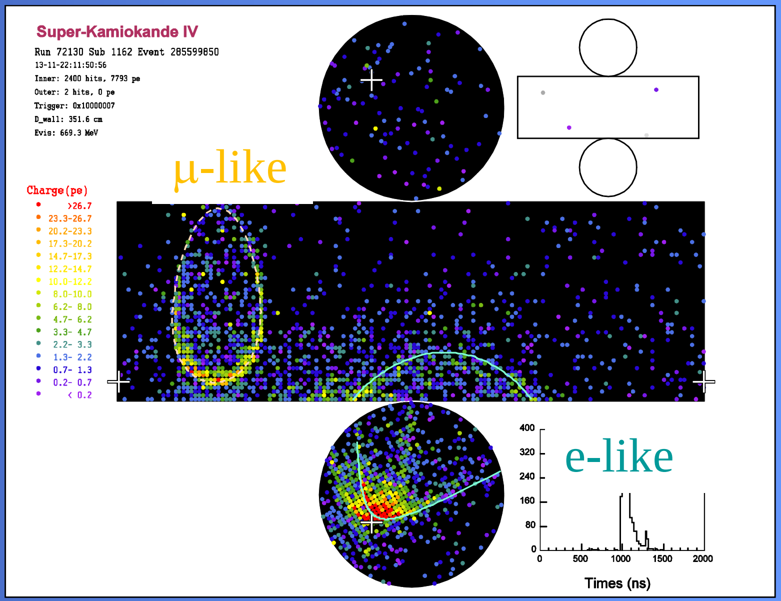
- Easy to construct large detector .
  - Need huge number of nucleons.
  - SK: 22.5kton in fiducail = 7.5×10^{33} protons.
- High efficiency and low uncertainty.
  - Mesons from proton decay in oxygen suffer from nuclear interactions (absorption, scattering, charge exchange …) which are dominant sources of inefficiency.
  - 2 hydrogens in water act as free proton, free from nuclear interactions.
- Backgrounds (atmospheric ν) are well understood.
  - SK is the world largest Neutrino Detection Experiment.

Observed events (both are 2-ring events)

1st event



2nd event



	TotMass (MeV/c^2)	TotMom. (MeV/c)	Pe (MeV/c)	Pμ (MeV/c)	Ang. (deg.)
1st	903	248	375	551	158
2nd	832	238	461	391	149

Note1: Cut: Ptot <250MeV/c, they were really close to boundary.
Note2: The 2nd event will go out from signal box with updated gain correction.

Systematic errors

	$p \to e^+\pi^0$		$p \to \mu^+\pi^0$	
	low P_{tot}	high P_{tot}	low P_{tot}	high P_{tot}
Eff.				
π-FSI	2.8	10.6	2.9	12.1
Corr. decay	1.9	9.1	1.7	9.0
Fermi mom.	8.5	9.3	8.0	9.6
Reconstruction	4.6	5.6	3.7	3.3
Total	10.2	17.7	9.4	18.2
BKG				
Flux	7.0	6.9	7.0	7.0
Cross section	14.5	10.4	8.4	7.8
π-FSI	15.4	15.4	14.2	14.4
Reconstruction	21.7	21.7	21.7	21.7
(neutron tag)	10	10	10	10
Total (I/II/III)	31.2	29.4	28.1	28.1
(IV)	32.7	31.1	29.9	29.8

Lifetime limt (90% CL) with 306kton・yrs data

$p \rightarrow e^+\pi^0$

> 1.6x10^{34} years

$p \rightarrow \mu^+\pi^0$

> 7.7x10^{33} years

(will be published soon).

Coming soon: Improved reconstruction tool.

- Current one: decide step by step: VTX, # of rings, PID, Mom …
- New method: Fit everything at once by maximum likelihood.
- Higher resolution → Expect to improve discovery potential.

Results of N→l+m

Mode	Eff. (Av,%)	BKG	Obs.	Poisson Prob ≥Obs (%)	Lifetime limit (10^{33}yrs)
$p \to e^+\eta$	25.8	0.78	0	-	10.0 (prev.4.2)
$p \to e^+\rho^0$	3.7	0.64	2	13.5	0.72 (0.71)
$p \to e^+\omega^0$	4.9	1.35	1	74.1	1.6 (0.32)
$n \to e^+\pi^-$	12.7	0.41	0	-	5.3 (2.0)
$n \to e^+\rho^-$	1.4	0.87	4	1.2	0.03 (0.07)
$p \to \mu^+\eta$	21.1	0.85	2	20.9	4.7 (1.3)
$p \to \mu^+\rho^0$	1.8	1.30	1	72.7	0.57 (0.16)
$p \to \mu^+\omega^0$	6.7	1.09	0	-	2.8 (0.78)
$n \to \mu^+\pi^-$	12.2	0.77	1	53.7	3.5 (1.0)
$n \to \mu^+\rho^-$	1.1	0.96	1	61.7	0.06 (0.036)

Consistent with BKG, lifetime limits improved factor 2~3 in most of modes.

PRD **91**, 072006 (2015)

$n\bar{n}$ oscillation

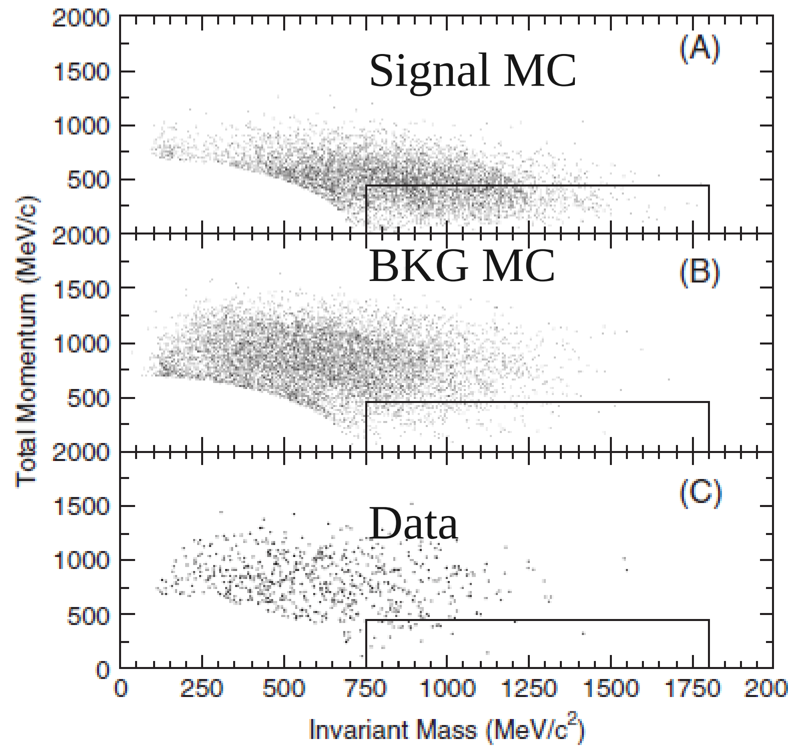
- $\Delta B=2$
- $\bar{n}$ annihilates immediately.
- Apply total momentum (P_{tot}< 450 MeV/c) and total mass cut (750 < M_{tot} <1800 MeV/c^2) to multi-ring.
- Use only SK1 data (91.7kton･yr).
  - ➢ Eff. 12.1 %
  - ➢ BKG: 24.1 events
  - ➢ Observed: 21 event
- Lifetime limt: > 1.9×10^{32}yrs

→ oscillation time (free neutron):

> 2.7×10^{8} sec

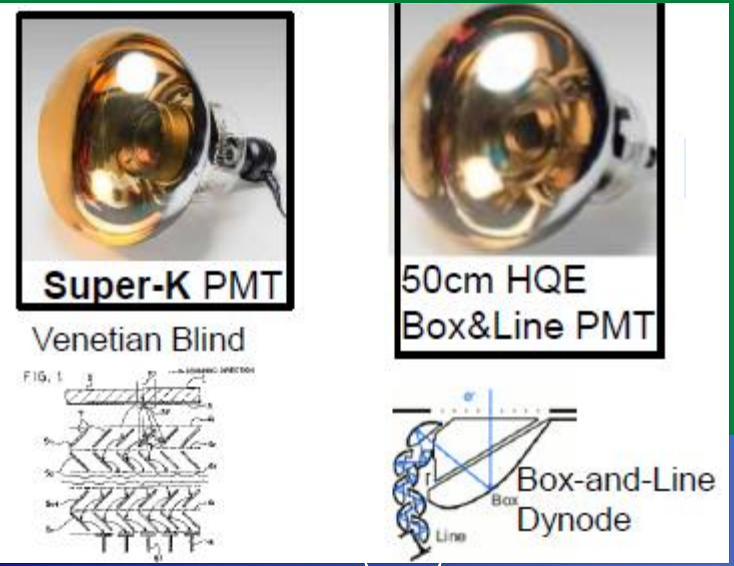
(using nuclear suppressing factor by Freedman&Gil, PRD 78, 016002(2008), with 20~30% theoretical error)

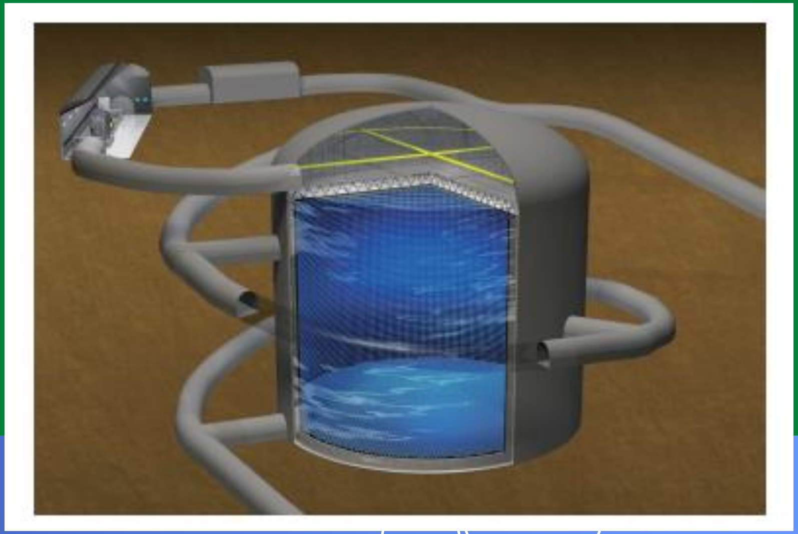
$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%



Current baseline design

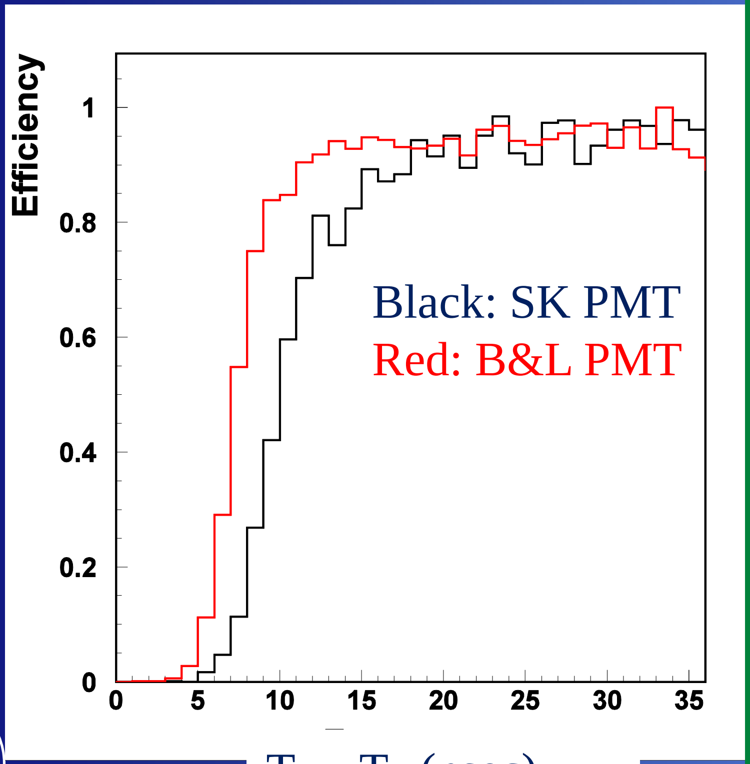
- Photosensor: Box&Line PMT, x2 photon counting efficiency, ½ time resolution than SK PMT.
- Photo-coverage: 40 %, same as the current SK.
- Tank size: 60m (H)x74m(D), upright cylindrical.
- Starting budget request for the first tank.





Impact of Box&Line PMT

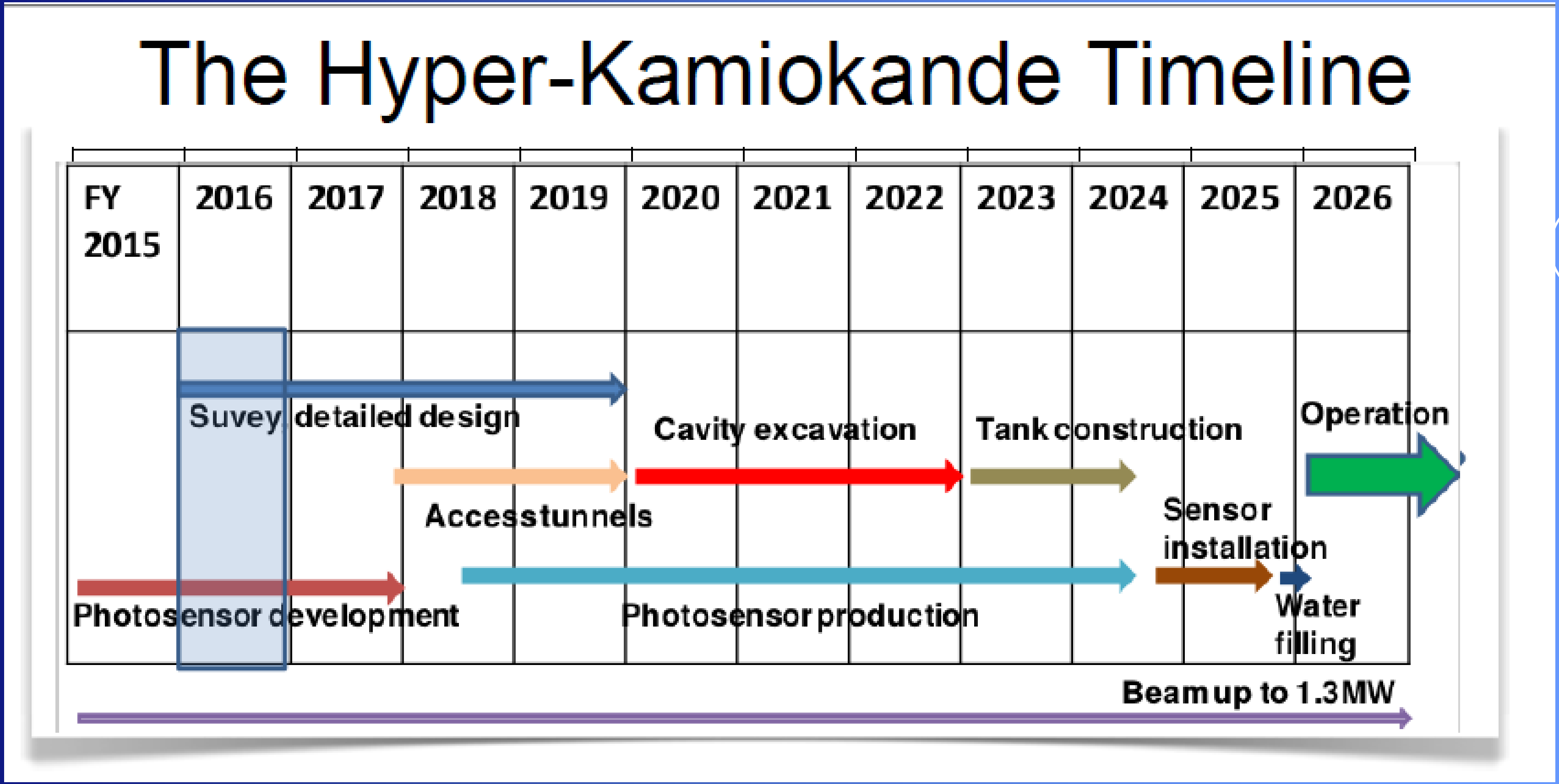
Efficiency curve of prompt γ tagging in p→νK$^+$



Tμ –Tγ (nsec)
~ K$^+$ decay time

- γ signal could be hidden by μ from K$^+$ decay if time difference is short.
- If time resolution is improved, more γ close to μ can be detected.
- Selection efficiency of p→νK$^+$γ will be increased by 44% and background events are reduced by 33% than SK due to new PMT.

→ Not only volume but performance is also improved.



Let's build Hyper-Kamiokande !

- Forming proto-collaboration.
- If you are interested in, contact to me.